Integrating Environmental Optics into Multidisciplinary, Predictive Models of Ocean Dynamics

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LONG-TERM GOALS

My long-term goal is the development of a data assimilative model system in which optical observations are linked directly and mechanistically to predictions of biological, chemical and physical dynamics of the ocean.

OBJECTIVES

The primary objectives are:

1. Continue to develop optical proxies for biological properties and processes in the upper ocean.
2. Establish a framework for modeling the dynamics of optical properties in the ocean, directly and mechanistically.
3. Integrate optical dynamics into state-of-the-art ocean models.

APPROACH

Optical proxies – The optical proxies that we are developing are metrics derived from optical measurements that can be related to directly to biologically important properties and processes. For example, the concentration of chlorophyll is estimated from proxies derived from measurements of ocean color, chlorophyll fluorescence, or spectral absorption coefficients. We extend the approach to include additional biological properties such as indicators of photosynthetic capabilities and biochemical composition, and to improve upon established procedures for retrieving estimates of phytoplankton abundance from measurements of ocean color and other optical properties. Data from deployments of coastal ocean observatories are used to develop and evaluate the models and bio-optical algorithms that define optical proxies. An extensive program of sampling from research vessels at our coastal observatories provides a large set of data for development and validation of bio-optical models for case 2 waters. Development of proxies for physiological properties (e.g., the irradiance to which phytoplankton are acclimated, a key measure of photosynthetic performance) depends on analysis of laboratory experiments in which photosynthesis, fluorescence and optical properties of phytoplankton are measured under a range of conditions.

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New modeling system – The photosynthetic pigment chlorophyll *a* plays a pivotal role in models of photosynthesis, phytoplankton dynamics, and optical variability in the ocean. During nearly 25 years of ONR-supported research, we have learned enough to propose a transition from long-established, chlorophyll-based models to a mechanistic system based on more directly relevant properties related to the absorption of light by phytoplankton (Cullen and Fennel 2010; Cullen 2011). Our approach is to develop an analog to a state-of-the art planktonic ecosystem model of medium complexity (e.g., Lima and Doney 2004), replacing all terms dependent on chlorophyll (either explicitly or implicitly) with new terms and functions that are mechanistically grounded in light absorption and utilization. An important benefit of this approach is that elements of the model can be constrained directly by optical observations via optical proxies described above.

Integrate optical dynamics into state-of-the-art ocean models – Our new modeling framework, including optical proxies, is being designed with a specific application in mind: a forecast system in which optical observations are linked directly and mechanistically to predictions of biological, chemical and physical dynamics of the ocean (Figure 1). Applications include remote sensing, surveys with autonomous ocean observing platforms including ocean gliders and profiling floats, and integration of observations from remote- and in situ sensor arrays. The technical approach is to collaborate with modelers who are working toward the development of data assimilative interdisciplinary forecast systems. During the reporting period, such collaboration was not directly supported.

This research program was an extension of a long collaboration with Marlon Lewis coordinated through the NSERC/Satlantic Industrial Research Chair in Environmental Observation Technology (IRC), a partnership between John Cullen (the Chair), Dalhousie University and Satlantic, Inc. (1995 - 2011). The Research Chair was leveraged with ONR support; it facilitated a broad range of collaborative research, including coastal observatories in Nova Scotia. The present ONR project provided funding for continued research conducted by members of the IRC research team who could be retained after the IRC program was terminated.

WORK COMPLETED

Sampling for optical properties. Bedford Basin was sampled weekly, with some dates missed, to collect oceanographic data related to phytoplankton and particle concentration, inherent and apparent optical properties, and nutrient concentrations. The data were quality controlled and depth averaged and stored on our data servers. The sampling is conducted in partnership with the Bedford Basin Plankton Monitoring Program, a nearly-20-year time series, conducted by Dr. W.K.W. Li of the Bedford Institute of Oceanography, and it is an extension of the Bedford Basin Ocean Monitoring Buoy (BBOMB) project coordinated by Susanne Craig, but suspended due to lack of funds. Continued sampling in Bedford Basin supports new research, including a project being developed by Dalhousie graduate student Mike Brown, who will study the influences of suspended sediments on optical properties of coastal waters.

Development of optical proxies. Analyzing data from Bedford Basin collected during the BBOMB project, Susanne Craig, Chris Jones and colleagues completed a study (see Craig et al. 2010) in which empirical orthogonal function (EOF) analysis of variations in ocean color effectively described the variation of chlorophyll *a* and the absorption coefficients of phytoplankton over a year in the coastal inlet (Craig et al. 2011). Continuing their efforts to develop a spectral, depth-integrated model of photosynthesis suitable for assessing the influences of solar irradiance and variations in spectral water

transparency on global primary production, Cullen, Yannick Huot and Richard Davis completed new analyses to calculate susceptibility of phytoplankton to inhibition of photosynthesis by ultraviolet radiation in the global ocean and developed an easily used software tool for examining the sensitivity of primary production to variations in the solar radiation and the optical properties of the water column (Cullen et al. 2011).

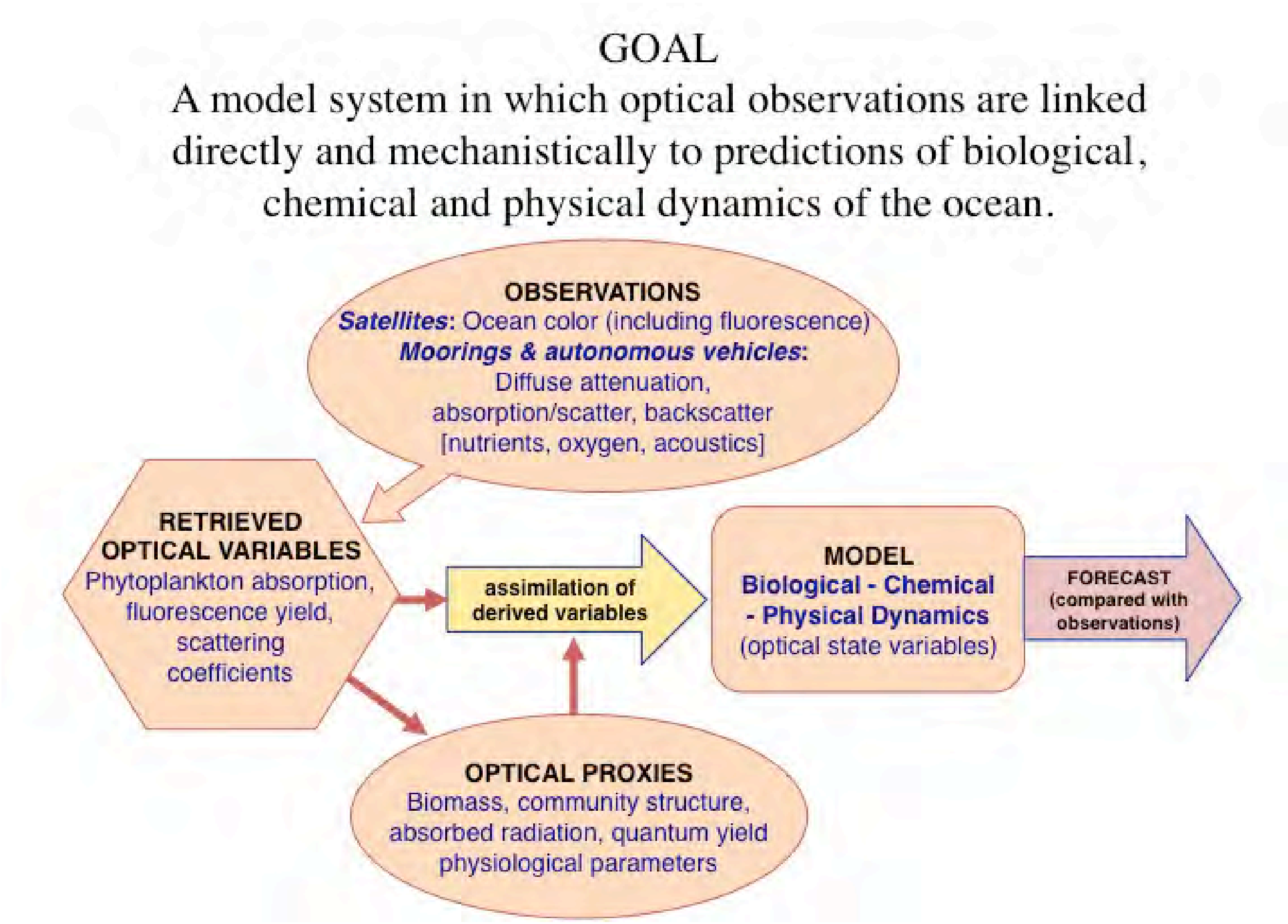

Figure 1. Conceptual framework for a data assimilative model system in which optical observations are linked directly and mechanistically to predictions of biological, chemical and physical dynamics of the ocean.

[Diagram: Observations from satellites, moorings and autonomous vehicles yield optical variables from which proxies of biological properties and processes are derived. The optical variables are assimilated into a coupled biological-chemical-physical model in which many of the state variables are optical, facilitating data assimilation, whereby forecasts are improved by quantitative comparison with observations.

Retrieval of physiological information using measurements from fluorometers. Audrey Barnett revisited results from a comprehensive series of experiments during which both variable fluorescence (PAM or FIRe fluorometer) and photosynthesis were measured as a function of irradiance for cultures of diatoms, an important group of phytoplankton. She conducted a thorough analysis and described the relationship between photosynthetic parameters and analogous measures based on fluorescence. These will be used in the interpretation of related metrics retrieved from fluorometers on ocean moorings and gliders, as analysed by Adam Comeau. Chris Jones and colleagues developed an analysis of photosynthesis *vs.* irradiance functions that include explicit consideration of processes that can be examined with modern fluorometers. Concurrently, Hugh MacIntyre analyzed a compilation of data on fluorescence and photosynthesis vs. irradiance to reveal complicating influences on the relationship between them that can be important in some groups of phytoplankton.

Absorption-based modeling of biological-optical dynamics. The framework for absorption-based modeling of phytoplankton dynamics, described by Cullen and Fennel at the Ocean Optics XX Meeting (Cullen and Fennel 2010), was refined and extended to include the effects of a limiting nutrient on chemical composition, making it suitable for implementation in models of medium complexity comparable to the one presented by Lima and Doney (2004). Also, the case for changing the way we model phytoplankton dynamics was presented in an invited lecture at Lamont Doherty's Earth Science Colloquium: "Chlorophyll *a* as the measure of phytoplankton biomass: Time to move on." The same message was presented during an invited symposium presentation at the C-MORE summer course in Microbial Oceanography at the University of Hawaii (Cullen 2011).

RESULTS

Analysis of an extensive set of optical and ground-truth data from the Bedford Basin Ocean Monitoring program showed that a rather simple Empirical Orthogonal Function (EOF) analysis of hyperspectral upwelling radiance measurements provided an excellent basis for predicting both the concentration of chlorophyll *a* and the contribution of phytoplankton to the absorption coefficient (Craig et al., 2010). Supplementary analyses conducted this year yielded important findings: i) normalization of the reflectance spectrum to its integral, i.e., analysis of spectral shape rather than magnitude, was key to success of the approach; ii) although hyperspectral spectra were analyzed, reduction of resolution to 8 wavebands had little effect; and statistical resampling tests showed that for this coastal environment, robust algorithms could be based on as few as 15 ground-truth samples of chlorophyll and absorption measurements, along with observations of ocean color, over a year (Craig et al. 2011). These results provide useful guidance for planning deployment and validation procedures for coastal ocean monitoring systems.

Results from our analyses of both fluorescence and photosynthesis vs. irradiance tell us that we are very close to being able to develop new fluorescence-based proxies for photosynthetic parameters (especially the irradiance at which photosynthesis approaches saturation, E_k). However, we are being very careful as we consider potential complicating factors. This takes time.

Although their development has been based on decades of published research, our depth-integrated, spectral model of photosynthesis and the absorption-based model of phytoplankton dynamics represent fundamental changes to the way primary production and the growth of phytoplankton are described in descriptive and predictive models. Time will tell if the new approaches are accepted.

IMPACT/APPLICATIONS

Our research is converging toward the development of an integrated system for using optically-based ocean observation assets — in particular, moorings, ocean gliders and satellite sensors — to guide multidisciplinary prediction of physical, biological and optical variability in surface layers of the ocean. We know that absorption-based modeling of phytoplankton dynamics has been an aspiration of oceanographers for decades; now we have a system for implementing it. In turn, our method for retrieving quantitative information about the physiology of phytoplankton from fluorometers on gliders is ready to be applied in our ongoing research. Simple analyses of hyperspectral radiometry will support the assessment of biological variability from space and will likely be applied in coastal monitoring. A significant impact on the science and systems applications of marine environmental prediction is highly likely. Progress will be rapid if the research is supported directly, but the impacts will be felt nonetheless.

RELATED PROJECTS

NSERC/Satlantic Industrial Research Chair: this partnership, strongly leveraged by ONR support of the collaboration between Marlon Lewis and John Cullen, was the focus of support for Cullen's research activities. The program terminated in early 2011 and this ONR grant supported follow-on activities.

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